Persistent-mode high-temperature superconductor shim coils: A design concept and experimental results of a prototype Z1 high-temperature superconductor shim

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Design, fabrication, and test results of a type persistent-mode high-temperature superconductor (HTS) shim coil are presented. A prototype Z1 rectangle-loop shim, cut from 46-mm wide Y-Ba-Cu-O tape manufactured by AMSC, was fabricated and tested at 77 K. The HTS shim, much thinner than the conventional NbTi shim, is placed inside the main magnet and immune to its diamagnetic wall effects. Combined with the >12 -T and >10 -K operation capability, the HTS shim offers a versatile design option for nuclear magnetic resonance (NMR) magnets, liquid-helium-free as well as conventional, and is particularly attractive in the next generation NMR magnets. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4816132>]

For the NMR (nuclear magnetic resonance) superconducting magnet, its field over a target space where a specimen (the object of spectroscopy) is placed must be very homogeneous. For a high-resolution NMR magnet, this inhomogeneity can be as severe as 0.01 ppm over a 30-mm diameter spherical volume (DSV). The “raw” field of most superconducting magnets is not good enough for NMR spectroscopy and therefore it must be shimmed to a homogeneous field over the specimen volume.^{1–3}

Generally, the superconducting NMR magnet is equipped with its own set of superconducting shim coils (“shims”), currently all wound with NbTi, a low-temperature superconductor (LTS). Because of their field limitations (<12 T even at 1.8 K) and size (typically 15–30 mm radial build), NbTi shims have always been located outside the magnet assembly, i.e., radially furthest away from the magnet center where the sample is placed. This is chiefly because no superconducting shims suitable for the high-field center region have been available. Here, we describe the design concept of the high-temperature superconductor (HTS) shims and results of a prototype Z1 shim, built and operated.

For a shim placed outside the magnet assembly, there are two inherent technical disadvantages: (1) at a great distance it must work *harder* to generate a required shimming field, i.e., a greater ampere (current)-turns (coil size); and (2) its field is *attenuated* by the “diamagnetic” walls of the magnet assembly, comprising many superconducting coils, as it reaches the magnet center. Worse, this field attenuation is asymmetric to the center and has strong hysteresis.

Diamagnetic effect is the manifestation of a screening current induced by a field impinging on a “Bean” cylinder.^{1,4–10} We may thus consider a superconducting coil as a Bean cylinder of a diamagnetic wall Δ thick.⁴ Although Δ cannot be equated directly to the size of a superconductor strand, typically ~ 50 μm for LTS and millimeters for HTS,

LTS coils generally have much less *attenuating* and *distorting* effects of the diamagnetic wall than HTS coils. However, a sheer size of LTS in a typical all-LTS NMR magnet makes diamagnetic effects in LTS magnets not negligible.

In this paper, we describe a design concept for superconducting shims prepared from a “wide” tape of coated YBCO HTS.^{11,12} The HTS shim can operate even in a >12 -T field and above *liquid helium* (LHe) temperatures.^{13,14} Slim (~ 1 -mm radial build), it can be placed *inside* the magnet assembly, avoiding the disadvantages inherent in the conventional NbTi shim. We believe that the HTS shim described here will become a key design option for NMR magnets, including those operated LHe-free, even at >4.2 K. Although not restricted to GHz-class NMR magnets,^{1,15–17} the HTS shim may find its application in these NMR magnets, because each >1 -GHz NMR magnet contains an insert of nested HTS coils, which may collectively be modeled as a thick-walled diamagnet.

To demonstrate the feasibility of this shim design, a prototype Z1 HTS shim, though the design is equally applicable to other shims, is prepared from a rectangle loop cut from a “wide” (currently 46 mm, and 100 mm in the near future¹⁸) YBCO coated conductor (tape) manufactured by AMSC. The tape, 80- μm thick overall, has a coating of a YBCO ~ 1 - μm thick film.¹¹

Figure 1(a) shows a drawing of a rectangle loop, 46-mm wide and $2\pi a + w$ long; Fig. 1(b) shows a Z1 shim of two rings with the two ends of the loop overlapped. The two ends may be overlapped (Fig. 1(c); adopted in Fig. 1(b)) or folded side-by-side (Fig. 1(d))—the arrows in (c) and (d) indicate current directions in the loop. Note that either way the $\pm z$ -directed current vectors are nearly canceled—more on this later.

Figure 2 shows the basic setup to energize a rectangle-loop shim. A pair of 4-mm wide YBCO strips serves as current leads; the red shades are joints. A section of the loop between the current terminals with a heater attached acts as a

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FIG. 1. (a) Drawing of a rectangle loop, laser-cut from a length of a 46-mm wide AMSC YBCO tape—each leg is w wide (here 4 mm) and δ thick; (b) schematic drawing of a Z1 shim folded from the rectangle loop of (a); (c) two loop ends overlapping—used in (b); (d) two loop ends placed side-by-side.

persistent-current switch. While the heated part of the loop remains resistive (Heater ON), the loop can be charged, I_{ch} . When the heater is turned OFF, the loop becomes superconducting, carrying a persistent-mode current, $I_l < I_{ch}$, that creates a *persistent-mode* shim field.

With a 46-mm wide YBCO tape currently available from AMSC, the maximum axial center-to-center distance for a Z1 shim is limited to 42 mm (for $w = 4$ mm) = $\sqrt{3}a$, or the maximum $2a$ of 48.5 mm. Note that for a Z1 shim comprising two rings, a gap distance of $\sqrt{3}a$ results in a Z1 field free of the Z3 (d^3B_z/dz^3) term.⁴ For $2a \geq 48.5$ mm, e.g., 74 mm ($\sqrt{3}a \simeq 64$ mm), two 36-mm wide (32 mm + 4 mm) tapes may be overlapped axially as illustrated in Fig. 3, which shows the current flow directions during energization for clarity, the two loops are shown not overlapped. Note that the solder joints (red shades) will not be in a persistent-mode circuit. As with two overlapping ends, any error fields generated by axial overlap will be negligible. Note that with a 100-mm wide tape, only one single loop will be required.

Figure 4 shows photos of a Z1 shim prototype, laser-cut from YBCO (1- μ m layer) sheet, 0.08-mm thick, 46-mm high, 156.4-mm wide, i.e., $2\pi a = 152.4$ mm, $w = 4$ mm: (a) the heater-current leads; (b) overlapping ends; and (c) the shim in a Styrofoam liquid nitrogen (LN2) dewar. The heater is made of stainless steel strip, 38 μ m-thick, 25-mm long, 4-mm wide.

The Z1 shim was tested in a bath of 77-K LN2. B_z vs. z plots, shown in Fig. 5, for two charging currents, $I_{ch} = 20$ A (black) and 40 A (red), give field gradients at $z = 0$, respectively, of 2.2 gauss/cm and 4.4 gauss/cm, that correspond to *persistent-mode* current, I_l , of 0.765 I_{ch} . A 23.5% reduction in I_l is reasonable from inductive energy consideration, i.e., when the persistent-current-switch is closed after the circuit has been charged to I_{ch} , a part of the circuit's inductive energy must now be transferred to the heater zone, which now carries I_l . Despite this inductive reduction, the 20-A and

40-A results demonstrate that it is possible to control shim current precisely. If operated at 4.2 K in its self field, the shim should be able to carry up to 500 A,^{13,14} generating a gradient field of ~ 50 gauss/cm, which corresponds to ~ 200 ppm of 1-GHz (23.5 T) field. Since the field by a loop current is inversely proportional to the loop radius, the 500 A $\times$ 1-turn single-loop HTS shim is equivalent to a 250-turn LTS shim of an average winding diameter 10 times that of the single HTS shim and operating at a typical maximum of 20 A. In a “high” (e.g., 30 T) axial background field, this Z1 shim will be subjected to large forces. Thus, the shim must be reinforced, e.g., a layer of 75- μ m-thick stainless steel strip helically wrapped over its entire axial length would be quite sufficient.

Figure 6 shows analytical $B_z(z)$ plots of three Z1 shim models (each of $2a = 48.5$ mm; 42-mm center-to-center) at a current of 500 A for: (1) two complete circular “bands,” each 4-mm (w) high (black); (2) overlapping (red dash); and (3) side-by-side (blue). Each plot shows the field along a helical path at $r = 15$ mm in the axial (z) range ± 30 mm. Note that higher order field errors, in the form of ripples, are discernible beyond ± 10 mm with the side-by-side Z1 shim.

In conclusion, a design for HTS shims that operate in *persistent mode* is proposed. A prototype Z1 shim, prepared with a rectangle loop cut from 46-mm wide YBCO coated tape manufactured by AMSC, was designed, built, and tested in a bath of liquid nitrogen at 77 K. Although not presented here, YBCO rectangle loops can be configured to build not only axial (Z1, Z2,...) but also radial shims (X, Y, ZX, ZY,...). The significant features of the HTS shim are (1) ability to operate in >12 T fields and at >10 K temperatures, both capabilities unachievable with the NbTi shim; (2) radial builds thinner than those of NbTi shims: <5 mm vs.

FIG. 2. With heater ON, the loop is charged (I_{ch}); with OFF, the entire loop becomes superconducting, establishing a persistent-mode current of I_l in the shim.

FIG. 3. Charging circuit of a two-loop Z1 shim.

FIG. 4. Photos of a Z1 shim prototype. (a) The heater leads; (b) overlapping ends; and (c) in a Styrofoam liquid nitrogen dewar.

FIG. 5. Measured $B_z(z)$ plots at 77 K of a Z1 shim.

FIG. 6. $B_z(z)$ plots of three Z1 shims.

>15 mm. A combination of these features enables an HTS shim to be placed inside the magnet assembly, i.e., closer to the specimen and immune to the detrimental diamagnetic wall effects of the superconductor in the main magnet. The HTS shim's ability to operate at >10 K makes it easily adoptable to LHe-free NMR magnets. This is a highly attractive feature in the next generation NMR magnet whose

operation will likely have to rely less and less on liquid helium. This persistent-mode HTS shim offers a versatile design option for NMR magnets, both LHe-relied and LHe-free.

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